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Development of SLA 3D printed volumes for leak testing of LHC Hi-Lumi cryomodules at STFC

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ABSTRACT

Daresbury Laboratory recently completed the build of a Radio Frequency Dipole (RFD) crab cavity cryomodule for the Super Proton Synchrotron (SPS). During the build the team faced challenges leak testing welds which could not be tested in the typical evacuation method. Each cryomodule build requires 34 unique cryogenic and insulation vacuum weld configurations, most of which are repeated across multiple weld sites. Each weld must be qualified inspected and tested (visual and leak) before the build can progress.

A suite of bespoke 3D printed weld test tools and procedures have been developed with major savings to time and cost and improved quality of leak testing tooling, developing a methodology which can be adapted to many different weld configurations. All whilst maintaining a baseline leak rate of <5e-12 mbar L/s at or below 1e-3 mbar. The result was a repeatable and cost-effective means of performing high-accuracy leak tests in a short timescale.

1. Introduction

The Large Hadron Collider (LHC) is the world's largest and highest-energy particle accelerator and will remain so for at least the next two decades. To extend its discovery potential the LHC will need a major upgrade in the 2020s to increase its luminosity and thus event delivery rate by a factor of five beyond its nominal design value. The integrated luminosity goal will be a ten-fold increase of the nominal design.

ASTeC (Accelerator Science & Technology Centre), Technology Department (TD) and the Cockcroft Institute (University of Lancaster), all based in Daresbury Lab (DL), have been tasked to play a key role in developing the superconducting Crab Cavity technologies for implementation on HL-LHC. Two crab cavity designs are being used; Double Quarter Wave (DQW) enabling vertical crab-crossing at the ATLAS detector interaction point and RF dipole (RFD), shown in Fig. 1, enabling horizontal crab-crossing at the CMS interaction point.

Fig. 1 displays the cryomodule with the Outer Vacuum Chamber (OVC) hidden. The cryomodule is comprised of two Superconducting Radiofrequency Crab Cavities, with connecting beam tubes. Surrounding this the cryogenic circuits can be seen to supply cryogenic fluids to the assembly to maintain superconductivity in the cavities. This assembly is affixed to a large top plate which acts as the interface for connecting Radio Frequency (RF) power, laser tracking and the cryogenic circuits to the wider system.

The project successfully completed manufacture of the first prototype cryomodule in 2023, to be tested in the SPS at CERN. The assembly process was extremely complex, and the team faced challenges in sequentially, and reliably, leak testing the assembly welds throughout the multi-year build process. Most welds could not be evacuated using the typical vacuum leak test method, meaning they could be tested to meet ISO20485 [1]. To resolve this challenge the team at DL, collaborating with CERN, saw an opportunity to use additive manufacturing technology to rapidly develop a reliable and effective leak testing solution.

The aim of this paper is report on the work and developments in vacuum technology completed to date during the build of LHC-HL

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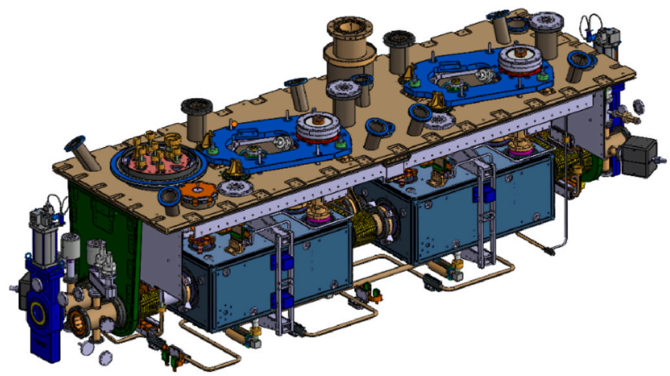

Fig. 1. View of RFD cryomodule – Outer Vacuum Chamber hidden.

cryomodules. This focusses specifically on the development and methodology of 3D printed volumes for leak testing, highlighting its functional capabilities to date and future avenues of research.

2. Vacuum acceptance criteria

Vacuum acceptance criteria is prescribed for both cryogenic and vacuum spaces described in Table 1.

The cryogenic welds cover the helium circuits and therefore require more stringent acceptance criteria than the insulating vacuum welds.

3. Design principles and prototypes

3.1. Design principle

The core of the ISO20485 leak testing methodology is in creating a vacuum pressure differential pressure (ΔP) across the weld, joint or test focus. This is achieved by evacuating the internal volume, then creating a helium pocket or atmosphere on the high-pressure side of the vessel.

The cryomodule build is broken down into twelve sequential steps with hundreds of sub-steps, including the welding. Each weld must be qualified by Visual Inspection and Helium Leak Test before the build can continue. Space constraints within the cryomodule pose a challenge for the leak tests access while creating a helium differential is difficult with open and incomplete cryogenic circuits and vacuum systems.

The proposed solution to this challenge is to flip the differential of pressure from the internal volume to the external side of the weld. This could be achieved with a small external volume which can then be sealed against the target weld site, illustrated in Fig. 2. Helium can then be backfilled into the test volume or sprayed onto the other side of the welded plate, to perform a compliant leak test. This technique has been previously established at CERN and its use on complex weld geometry has been covered using a device known as the Hood Clamshell [2,3].

3.2. Prototype testing

A stainless-steel prototype was developed around a large circumferential cryogenic weld on the cryomodule. This prototype consisted of two half "clamshells" which when sealed could be evacuated through a KF25 port welded to its body. The clamshell was manufactured from 316L stainless-steel. The two half volumes were sealed using Tacky Tape® SM5144, a sealant tape typically used in vacuum bags for composite manufacture.

Table 1
Summary of leak test acceptance criteria.

Pressure Region	Vacuum Welds	Cryogenic Welds	Comments
<5 × 10^{-3} - 1 × 10^{-4}	<1E-09 mbar l/s	<1E-10 mbar l/s	Assuming unbaked system

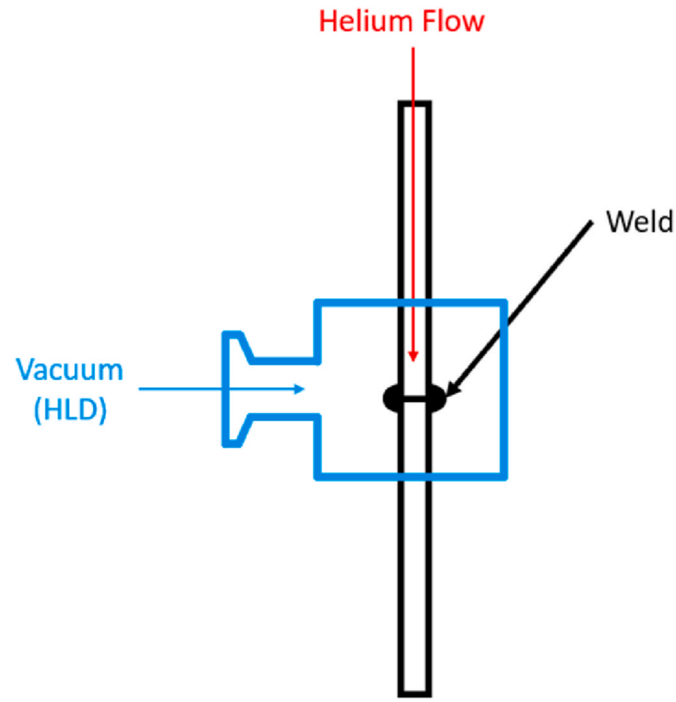

Fig. 2. Illustration of proposed ΔP volume configuration.

The test schematic can be seen below in Fig. 3. The volume is evacuated with a helium leak detector unit (Leybold Pheonix Vario), helium is then cycled into the test volume, sufficient time is given to ensure a best possible helium atmosphere concentration, and a small positive pressure is then achieved. The leak rate is then measured through the leak detector unit.

Initial testing seen in Fig. 4 was a success. The volume was sealed, and generated a baseline leak rate in 1e-11 mbar L/s. Following from this, a second leak test interface described as a "differential pressure volume" was created to test a planar weld configuration using the same principle, Fig. 4, right. Note also that for the test on the right, a generic brand of vacuum sealing tape was used, although it produced satisfactory results all other tests were performed with SM5144 tacky-tape for continuity.

Both tests were a success and produced satisfactory leak rates, however there were some clear improvements. Firstly, in the designed clearances – The clamshells seal best when minimal clearance, or tolerance, is given. They should be as close to an exact fit as possible; In conjunction with this, as little sealant tape should be used as possible - too much creates trapped volumes which affect the achievable baseline leak rate.

Material selection was also highlighted as a key area for improvement. Whilst the trial was effective, large stainless-steel volumes were impractical, expensive, wasteful to manufacture, and could easily damage the cryomodule. 3D printed parts [4] and chambers are becoming more relevant within vacuum technology [5,6] and the characterisation of commercially available plastics is being reported, with Stereolithography (SLA) being the most promising method of 3D printing plastics [7,8]. Therefore, 3D printing is a logical solution to this and through the CERN collaboration, an SLA based material was suggested as suitable for vacuum use – Accura25.

Accura25 is a "Polypropylene like" plastic. The parts are manufactured using Stereolithography (SLA) 3D printing, a versatile and highly accurate method of printing [9]. The material properties used in the simulation and production parts are derived from material datasheets produced by the material supplier - 3Dsystems [10]

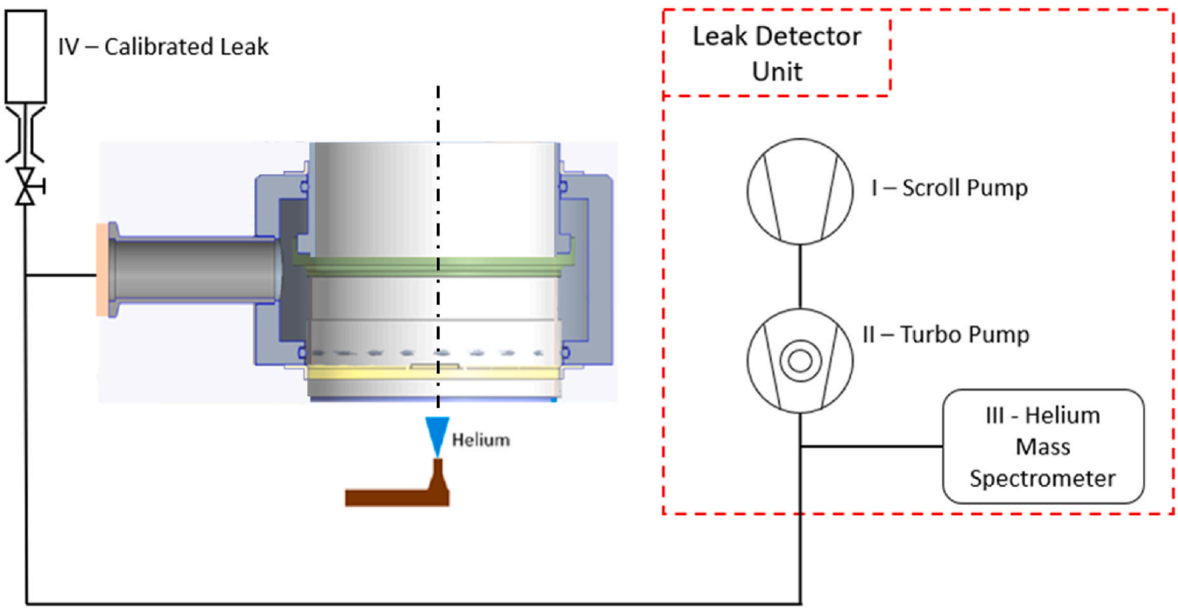

Fig. 3. Clamshell test schematic.

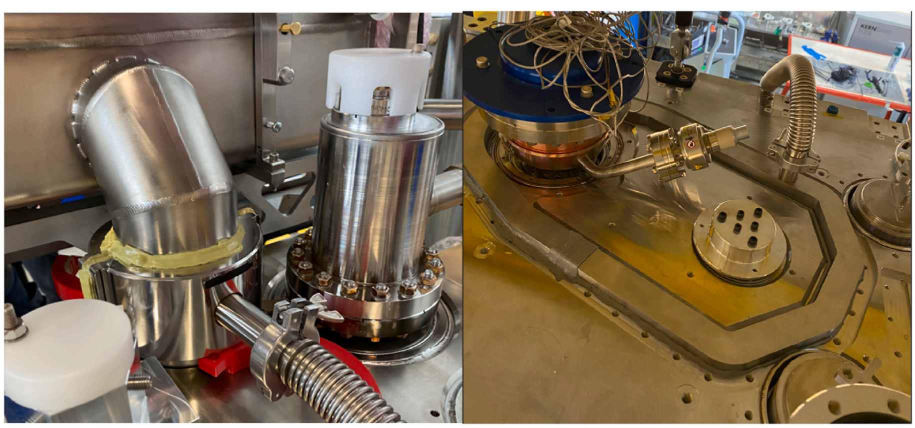

Fig. 4. Prototype Clamshell (left) & Prototype planar differential pressure volume (Right).

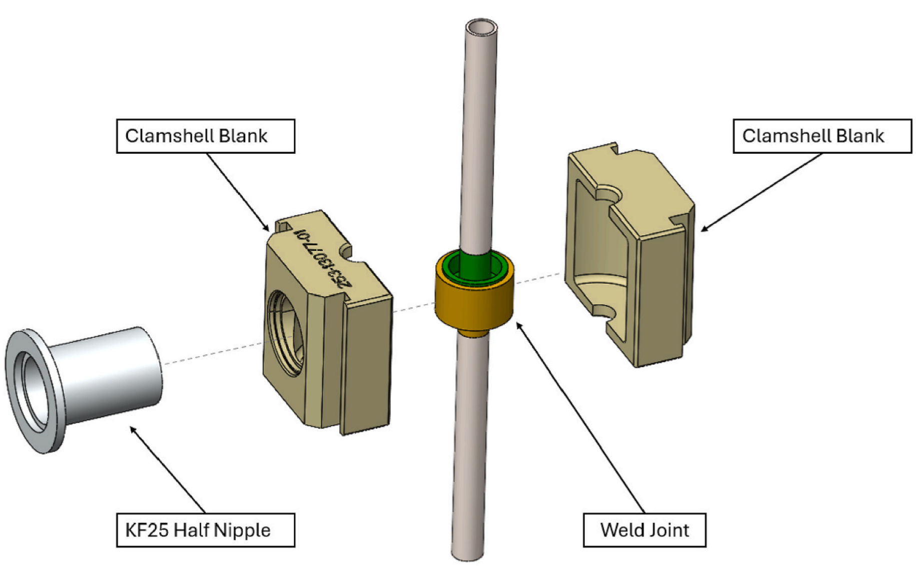

Fig. 5. Exploded view of typical test configuration.

4. 3D printed volumes

4.1. Accura25 clamshells

Using the same design principals of the original Stainless Steel prototype, SLA 3D printed clamshells were trialled on the smaller welds on the cryomodule. The converged design consists of two half volumes, with minimal clearance, which are then sealed with Tacky Tape®, or equivalent vacuum bag sealant. An aluminium KF25 port is then epoxied into the body using a low outgassing epoxy, an exploded view is seen in Fig. 5.

Blank tests were conducted to test the baseline leak rate of the volumes. With minimal use of vacuum tape, baseline leak rates of 1e-12 mbar L/s was easily achieved, with a set up & pumping time of <20 min, easily reaching a range of 1e-3 to 5e-4 mbar pressure with minimal surface preparation. Measured using the leak detector internal full range gauge. No virtual leaks were noted with the KF insert. The assembly staged of the test setup is shown in Fig. 6.

The use of a sealing tape over the use of traditional vacuum compounds, which closer resemble a clay, is preferable as the adhesive nature of the tape provides a benefit in holding the assembly together without the requirement for any clamping load.

Accura25 or other SLA plastics represent a rapid and cost-effective means of developing bespoke leak test tooling for any complex weld geometries.

4.2. Volumes for complex geometry

With the support of the TRIUMF collaboration, the suite of clamshells has been expanded. Over 30 unique geometries have been developed to cover all welds across the cryomodule, all constructed from 3D printed Accura25. Fig. 7 shown below, is an example of a complex planar weld which was able to be easily leak tested after welding. The two halves were sealed against each other to form an encompassing chamber.

Whilst a number of these welds could be tested at the end of the assembly process, the risk of failure & cost of disassembly, correction, and reassembly after a year-long build process is too great to be considered.

All volumes are of a 5 mm wall thickness as standard, increasing where required, and are validated using Finite Element Analysis (FEA) in ANSYS for their mechanical performance and to inform the design approach. All parts were designed with a minimum factor of safety (FOS) of 3.5. Derived from Ref. [10], select material properties of Accura25 can be seen in Table 2 below.

Accura25 is suitable for parts up to diameters of 150 mm, in a typical cylindrical part, without the requirement for any specific supports or complex design features. At and above 150 mm diameter, draft angles (a term used to describe a tapered internal feature, commonly seen in injection mould tooling) and internal supports & thicknesses should be added to maintain structural integrity under vacuum, such as that seen in Fig. 8. Whilst not as strong as traditional materials such as stainless-steel or aluminium, Accura25 is appropriate for all small vacuum testing configurations present in the LHC-HL cryomodule build.

5. Results

The clamshells were tested on 11 welds across the cryomodule build. As this development began mid-build, only a selection of welds were tested with this process. The base pressure and baseline leak rate of all tests are shown in Table 3 below. The results have been highlighted as yellow & green to differentiate between satisfactory results (within specification) and very good results (measured in −12 mbar l/s decade).

In addition to these experimental results, a catalogue of 34 3D printed clamshells have been designed to be printed and used on upcoming double quarter wave (DQW) & RFD series crab cavity cryomodules. All designs were thoroughly validated using ANSYS Static simulations and a standard factor of safety of 4 was used as a limit to allow plenty of material strength even accounting for small imperfections during manufacture. An example of the simulation can be seen in Fig. 8. The contours in green & yellow show areas of high stress, displayed values are the Factory of Safety (FoS) of the part. This is a unitless number which represents how close to failure a part will be under its designed load. In this case the minimum FoS is 3.5, meaning that the part can sustain 3.5x its designed load before failure.

The most common design takes the form shown in Fig. 9 below, with variations to its size to suit its corresponding weld. Other designs take the form shown in Figs. 7 and 8 (see Fig. 10).

6. Discussion

The results from Table 2 highlight a comparison between clamshells of a typical stainless-steel construction and that of a 3D printed Accura25 construction. Whilst the principle of a differential pressure is well established, it is interesting to note that the use of 3D printed plastics, with little surface preparation, in place of traditional materials showed no measurable reduction of leak test accuracy, or performance, within the measurable deviation of the helium leak detector used.

Some caveats must be noted before drawing conclusions. The stainless-steel clamshells were prototype clamshells with larger clearances than the Accura25 versions. This created more difficulties creating a good seal around the joint when compared to later versions. If these clamshells had minimal tolerance in the assembly, then they would have certainly achieved lower baseline leak rates, however this would come at an increased cost of manufacture. It is important to also note that

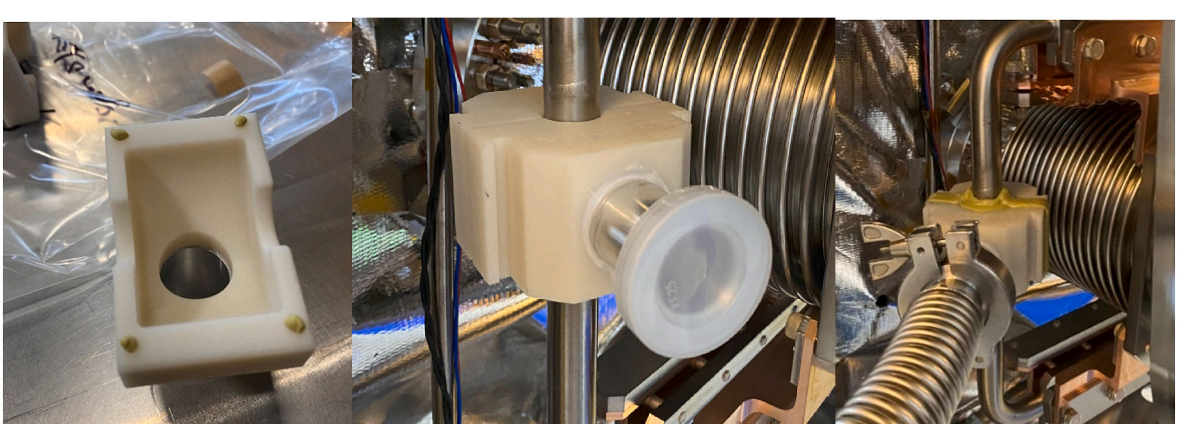

Fig. 6. Accura25 clamshell configuration.

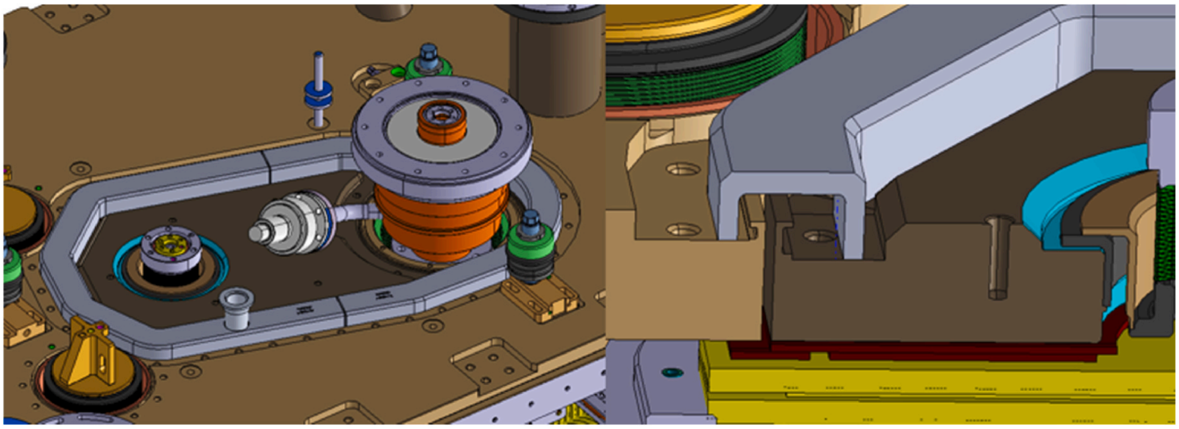

Fig. 7. Example of geometries for planar welds.

Table 2
Select material properties of Accura 25.

Measurement	Condition	Value
Tensile Strength (MPa)	ASTM D 638	38
Tensile Modulus (MPa)	ASTM D 638	1590–1660
Elongation at Break (%)	ASTM D 638	12–20
Flexural Strength (MPa)	ASTM D 790	55–58
Flexural Modulus (MPa)	ASTM D 790	1380–1660

these tests were performed using a calibrated helium leak detector only using its internal pressure gauge and mass spectrometer, it is not possible to comprehensively compare the stainless steel and Accura25 with the data gathered at this stage. A more accurate vacuum system is required for detailed analysis of the material and its properties is required, which was not available at this stage of the project.

Taking this into account however, we can see that Accura25 clamshells performed equally as effectively within the sensitivities of the helium leak detector for this application. Notably once a method of working was established, the 3D printed clamshells regularly achieved a baseline leak rate <5E-12 mbar l/s, demonstrating their suitability for high accuracy helium leak detection.

From these positive results a full suit of 34 leak testing volumes have been developed to qualify all welds across the cryomodule, and all volumes are designed with a minimum factor of safety of 4. The use of Accura25 represents approximately a 50 % reduction in tooling costs for the leak tests, priced from local suppliers.

Whilst not better than stainless-steel or aluminium, in terms of vacuum performance, it is comparable in this application. SLA 3D printing represents an effective and cost reducing alternative to subtractive manufacturing methods for acceptance testing of complex assemblies. However, more work is required to characterise this material further in terms of its vacuum performance and suitability for high vacuum applications such as has been performed for other 3D printed materials [11,12]. The material and the sealing compounds used for this test has not been thoroughly examined for their outgassing rates, nor the gas species which may be introduced from these materials. As a result of this it is not possible to discuss how the materials outgassing properties relate to, and effect, the system pressure.

Table 3
Clamshell Leak test results.

Weld number	Test Pressure (mbar)	Baseline Leak rate (mbar l/s)	Clamshell Material
Clamshell 1	9.50E-04	9.90E-10	Stainless-Steel
Clamshell 2	8.57E-04	2.00E-12	Stainless-Steel
Clamshell 3	8.37E-04	1.40E-10	Stainless-Steel
Clamshell 4	1.35E-03	6.10E-11	Stainless-Steel
Clamshell 5	3.98E-03	1.30E-10	Accura25
Clamshell 6	2.00E-03	1.30E-12	Accura25
Clamshell 7	2.25E-03	5.17E-10	Accura25
Clamshell 8	9.47E-04	1.30E-12	Accura25
Clamshell 9	2.01E-03	1.04E-12	Accura25
Clamshell 10	8.01E-04	1.03E-12	Accura25
Clamshell 11	1.14E-03	1.20E-12	Accura25

Note – The minimum detectable leak rate of the Pheonix Vario is given as 5e-12 mbar l/s. The results given in Table 2 are the raw values produced by the leak detector during the test, these have been maintained for completeness, but shall be considered as <5e-12 mbar l/s for discussion.

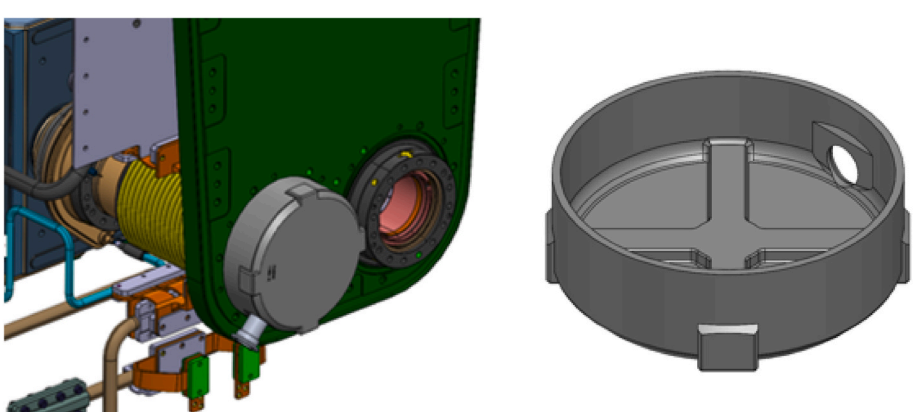

Fig. 8. Planar weld differential pressure volume.

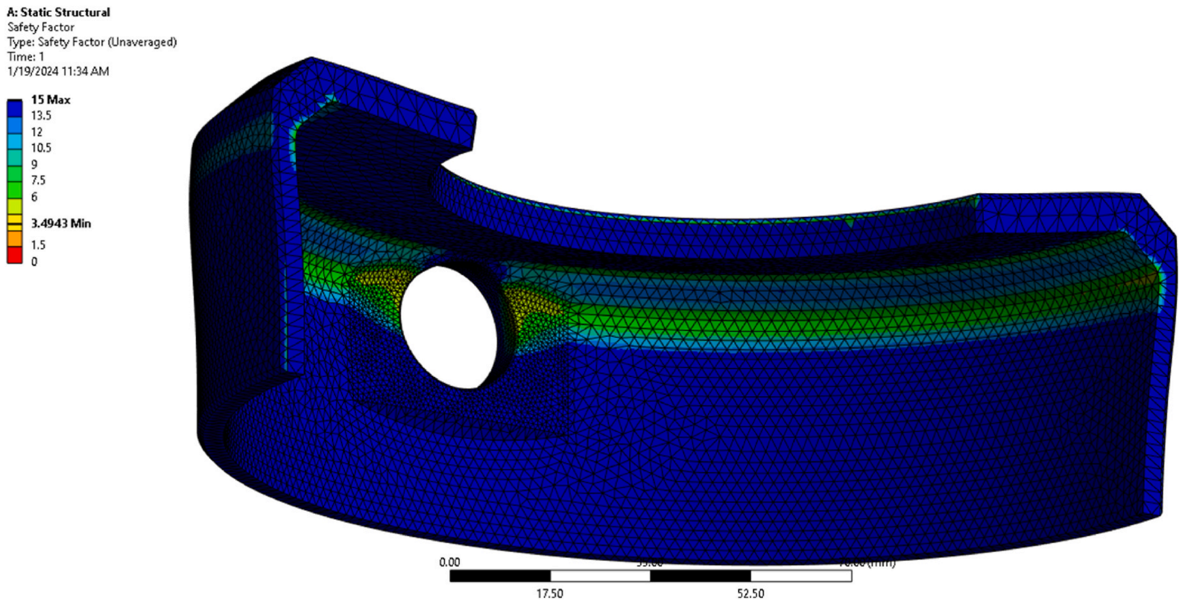

Fig. 9. ANSYS simulation results for a leak testing volume.

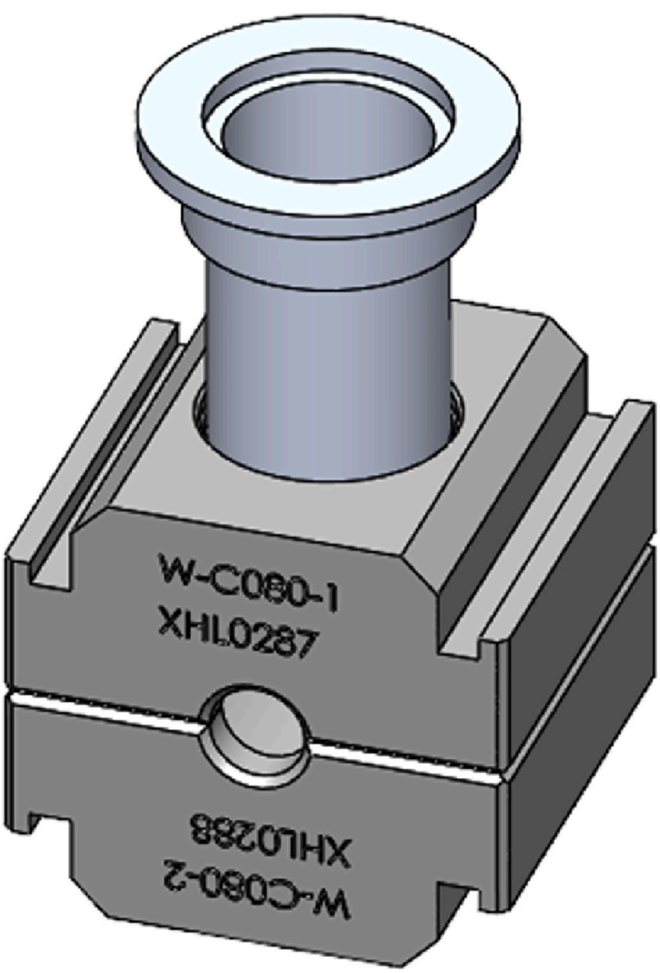

Fig. 10. Typical clamshell assembly.

7. Conclusion

A suite of bespoke 3D printed weld test tools and procedures have been developed with major savings to time and cost and improved quality of leak testing tooling, developing a methodology which can be adapted to many different weld configurations. All whilst maintaining a baseline leak rate <5e-12 mbar L/s at and within the 1E-03 to 1E-04 mbar vacuum range. The result was a repeatable and cost-effective means of performing high-accuracy leak tests in a short timescale.

The use of SLA 3D-printed alternative materials represents a significant avenue of development for vacuum technologies and vacuum testing. The ability to rapidly manufacture bespoke leak test tooling has not only reduced costs but also improved the accuracy of intermediate testing stages. Accura25 crosses into the high vacuum pressure range with little surface preparation beyond alcohol wipes. There is clear value in continuing to assess this material through outgassing testing and RGA spectrum analysis to fully characterise Accura25 and its potential uses in high vacuum systems at STFC.

A new package of work is also underway to further characterise the material for vacuum applications and to assess the viability of 3D printed pumping ports. In addition, the project team is adapting the tooling for the DQW Cryomodule manufacture process.

CRediT authorship contribution statement

J.O.W. Poynton: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **S. Wilde:** Writing – review & editing, Methodology, Conceptualization. **J. Bourne:** Conceptualization. **E. Jordan:** Project administration, Conceptualization. **N. Templeton:** Writing – review & editing, Resources, Project administration. **B. Matheson:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Formal analysis. **T. Capelli:** Project administration, Conceptualization. **A. Seller:** Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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